Probing the Deuteron Structure at small NN Distances by Antiproton-Deuteron Annihilation *

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Abstract

The annihilation $\bar{p}d \to 2\pi^-\pi^+p$ at rest is analyzed. Assuming that the deuteron wave function can be represented by the Fock's column consisting of different possible states ($NN, NN^*, \Delta\Delta, NN\pi$,...) some enhancement in the distribution over the invariant mass of the $\pi^-\pi^-$ system in the mass region $1.4 - 1.5(GeV/c^2)$ is predicted. This can be caused by the possible existence of a $\Delta - \Delta$ component in deuteron. Using this prediction and new experimental data of the OBELIX collaboration (LEAR, CERN) one can estimate the upper limit for this exotic state of deuteron.

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Over the past decades the deuteron structure at short distances has been investigated rather intensively. There are many theoretical approaches trying to study this problem. For example, within the quark model picture the admixture of 6q-components has been suggested [1, 2]. This corresponds to an admixture of baryon resonances within the asymptotic basis of baryonic states $(N(938), \Delta(1232), N^*(1440), ...)$ [3, 4]. New information about the existence of, for example, $NN^*(1440)$ in a deuteron can be obtained by studying subthreshold antiproton production in pd and dd reactions [5]. It was shown that the probability of this component in a deuteron can be less than 0.5%. Attempts to detect baryon resonances in a deuteron were made by many experimental groups [6, 7] and [8, 9]. As a rule, pion, photon, neutrino and proton beams of intermediate energy together with fixed target setups were used for this purpose. These groups have tried to demonstrate the presence of N^* in nuclei by shaking loose an N^* that preexists in the nucleus acting as a spectator in some reactions. The main problem for such experiments was to distinguish between the signal from the internal N^* and the signal from another states produced by the conventional way, e.g. via rescattering. The experimental results are given as upper limits, ranging in $(0.4 \ - \ 0.9)\%$.

We propose alternatively to explore antiproton annihilation on the deuteron to provide new information on the possible existence of the above mentioned states in the deuteron. Here we are intend well known measurements of $\bar{p}d$ annihilation at rest performed by the OBELIX collaboration (see e.g. [10]). New data obtained by this experiment [11] show the very interesting behavior of the $\pi^-\pi^-$ system invariant mass distribution in reaction $\bar{p}d \to 2\pi^-\pi^+p$. In this paper we concentrate on detailed analysis of this annihilation channel. We show also that some enhancement in the spectrum over the invariant mass of two π^--mesons observed by OBELIX can be explained by the possible existence of a $\Delta - \Delta$ component in the deuteron.

The general expression for the differential cross section $d\sigma/dm_{2\pi}$ for the above mentioned annihilation reaction in flight within the framework of the impulse approximation, see Fig.1, can be written in the following form:

$$\frac{d\sigma}{dm_{2\pi}} = \frac{2m_{2\pi}}{(2\pi)^8 2\lambda^{1/2}(s, m^2, M_d^2)} \int ds_{3\pi} R_2(s, m^2, M_d^2) R_3(s_{3\pi}, m_n^2, m^2) \qquad (1)$$
$$\mid T_{\bar{p}d \to 2\pi^-\pi^+p}(s, s_{3\pi}, t, t_1) \mid^2$$

where the following notation is introduced: $m_{2\pi}$ is the invariant mass of two pions; $\lambda^{1/2}(x, y, z) = (x - (\sqrt{y} - \sqrt{z})^2)^{1/2}(x - (\sqrt{y} + \sqrt{z})^2)^{1/2}$; s is the square initial energy in the $\bar{p} - d$ c.m.s.; $s_{3\pi}$ is the square invariant mass of three pions; m, M_d are the masses

of the nucleon (antinucleon) and the deuteron, respectively; m_n is the mass of the neutron inside the deuteron which, in principle, is off-shell; $R_2(s, m^2, M_d^2)$ is the two-particle relativistic invariant phase-space for the binary process $\bar{p}+d \to 3\pi+p$ when in the final state there are a proton and a particle with the invariant mass of three pions; $R_3(s_{3\pi}, m_n^2, m^2)$ is the three-particle relativistic invariant phase-space for annihilation of the initial antiproton on the intra-deuteron neutron $\bar{p}n \to 2\pi^-\pi^+$; $T_{\bar{p}d\to 3\pi p}(s, s_{3\pi}, t, t_1)$ is the amplitude of the process $\bar{p}d \to 2\pi^-\pi^+p$, $t = (p_d - p_p)^2$, where p_d, p_p are the four-momenta of the initial deuteron and final proton, respectively; $t_1 = (p_{\bar{p}} - p_\pi)^2$, where $p_{\bar{p}}, p_\pi$ are the four-momenta of the $\bar{p}$ and of the final pions, respectively.

Within the framework of the impulse approximation, see Fig.1, this amplitude can be written in the factorized form:

$$T_{\bar{p}d\to 3\pi p}(s, s_{3\pi}, s_{2\pi}, t, t_1) = \phi_d(\mathbf{p}_p(s,t)) f_{\bar{p}n\to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \tag{2}$$

where ϕ_d and $f_{\bar{p}n\to 2\pi^-\pi^+}$ are the deuteron wave function and the amplitude of the annihilation process $\bar{p}n \to 2\pi^-\pi^+$; $\mathbf{p}_p$ is the three-momentum of the final proton. Now, inserting now expressions for R_2, R_3 [12] and $T_{\bar{p}d\to 3\pi p}$ given by eq.(2) into eq.(1) one can get the following form for the distribution over the invariant mass of the $\pi^+\pi^-$-pair:

$$\frac{d\sigma}{dm_{\pi^+\pi^-}} = \frac{2m_{\pi^+\pi^-}\pi^3}{2(2\pi)^8 2\lambda(s, m^2, M_d^2)} \frac{1}{2\lambda^{1/2}(s_{\pi^+\pi^-}, \mu^2, \mu^2)} \int ds_{3\pi} \int \frac{dt}{2\lambda^{1/2}(s_{3\pi,t,m^2})} \tag{3}$$
$$\mid \phi_d^2(p(s(t)) \mid^2 \int dt_1 \int ds_{2\pi^-} \mid f_{\bar{p}n\to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2$$

A similar expression can be written for the distribution over the invariant mass of the $\pi^-\pi^-$-pair:

$$\frac{d\sigma^1}{dm_{\pi^-\pi^-}} = \frac{2m_{2\pi^-}\pi^3}{2(2\pi)^8 2\lambda(s, m^2, M_d^2)} \frac{1}{2\lambda^{1/2}(s_{2\pi^-}, \mu^2, \mu^2)} \int ds_{3\pi} \int \frac{dt}{2\lambda^{1/2}(s_{3\pi}, t, m^2)} \tag{4}$$
$$\mid \phi_d^2(p(s(t))) \mid^2 \int dt_1 \int ds_{\pi^+\pi^-} \mid f_{\bar{p}n\to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2$$

where $s_{2\pi} = m_{2\pi}^2$ is the square invariant mass of $2\pi^-$, μ is the pion mass. For calculation of the spectra given by eqs. (3), (4) the amplitude of the annihilation $\bar{p}n \to 2\pi^-\pi^+$ should be known.

Actually, the question arises how to calculate the amplitude $f_{\bar{p}n\to 2\pi^-\pi^+}$. It was parametrized by a form that resulted in a satisfactory description of the experimental data for $dN/dm_{\pi^+\pi^-}$. According to the OBELIX data [11] the spectrum $dN/dm_{\pi^+\pi^-}$

has a resonance-like shape, see Fig.2, corresponding to the possible production of ρ-meson at $m_{\pi^+\pi^-} \simeq 0.77(GeV/c^2)$ and f_2-meson at $m_{\pi^+\pi^-} = 1.26(GeV/c^2)$. The dependence of $\mid f_{\bar{p}n \to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2$ on $s_{\bar{p}n} = s_{3\pi}$ can be found using the model of the Reggeized meson exchange in the t-channel of the reaction $\pi^+ n \to \pi^+\pi^- p$, where $t > 0.$ and $t = (p_n - p_p)^2 = (p_n + p_{\bar{p}})^2 \equiv s_{\bar{p}n} = s_{3\pi}$. The t_1-dependence of $\mid f_{\bar{p}n \to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2$ can be found using the usual one-baryon exchange model of the reaction $\bar{p}n \to 2\pi^-\pi^+$. Therefore, the square of the amplitude $f_{\bar{p}n \to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1)$ has been parametrized by the following form:

$$\mid f_{\bar{p}n \to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2 = B^2(s_{\pi^+\pi^-}) \frac{s_{3\pi}}{(s_{3\pi} + \mu^2)^2} F_1^2(s_{3\pi}) \frac{\mid t_1 \mid}{(\mid t_1 \mid + m^2)^2} F_2^2(t_1) \tag{5}$$

where $F_1(s_{3\pi})$ is the pion form-factor corresponding to the $NN\pi$-vertex by the Reggeized meson-exchange of $\pi^+ n \to \pi^+\pi^- p$ process, it can be parametrized by the usual form $F_1(s_{3\pi}) = exp(-s_{3\pi} R_\pi^2)$ where the parameter $R_\pi^2 \simeq 2GeV^{-2}$ [13] is used; $F_2(t_1)$ is the baryon form-factor corresponding to the $NN\pi$-vertex by the one-baryon exchange in s-channel of the reaction $\bar{p}n \to 2\pi^-\pi^+$, it was taken in the form $F_2(t_1) = \Lambda_B^2/(\mid t_1 \mid + \Lambda_B^2)$ where $\Lambda_B = 0.4 - 0.5(GeV/c)^2$ [14]; $B(s_{\pi^+\pi^-})$ is the function corresponding to the resonance and nonresonance mechanisms of the annihilation process $\bar{p}n \to 2\pi^-\pi^+$, it was parametrized by the following form:

$$B(s_{\pi^+\pi^-}) = \frac{w_\rho}{\sqrt{s_{\pi^+\pi^-}} - m_\rho - i\Gamma_\rho/2} + \frac{w_{f_2}}{\sqrt{s_{\pi^+\pi^-}} - m_{f_2} - i\Gamma_{f_2}/2} + iw_0 \tag{6}$$

Really, the form (5) is some parametrization of the square of the amplitude of the process $\bar{p}n \to 2\pi^-\pi^+$, and application of the Reggeized one-boson exchange model can be considered only as a prompt to find the parametrization form (5).

Now, inserting eq.(5) into eq.(3) one can calculate the spectrum $d\sigma/dm_{\pi^+\pi^-}$. Experimental measurements of this spectrum were performed at rest and presented in [11]. Therefore, the spectrum given by eq.(3) was calculated at a very small initial antiproton energy satisfying to the experimental resolution and normalized by the total number of events, N, corresponding to experimental measurements. This spectrum $dN/dm_{\pi^+\pi^-}$ and the experimental data are presented in Fig.2, the parameters w_ρ, w_{f_2}, w_0 and R_π^2 were found by fitting the OBELIX experimental data [11] for $dN/dm_{\pi^+\pi^-}$, they are $w_\rho = 1.2, w_{f_2} = 1.35, w_0 = 35.0$ and $R_\pi^2 \simeq 2.(FeV/c)^{-2}$.

Now, inserting the same form for $\mid f_{\bar{p}n \to 2\pi^-\pi^+}(s_{3\pi}, s_{2\pi}, t_1) \mid^2$ given by eq.(5) into eq.(4) one can calculate the spectrum $dN/dm_{2\pi^-}$ which is presented in Fig.3 (the dashed curve) together with the experimental data [11].

Now, consider the problem related to the possible existence of baryon resonances in a deuteron. There is a point of view [15, 16] that a deuteron wave function (d.w.f.) can be considered a Fock column the lines of which are $NN, \Delta\Delta, NN^*, NN\pi$, etc., components. There are theoretical models within the framework of which the d.w.f. is considered taking into account these baryon resonances in a deuteron. We used one of these models [1, 2] in order to estimate the upper limit of the probability for a $\Delta\Delta$-component to exist in the deuteron. The possible mechanism of the annihilation $\bar{p}d \to 3\pi p$ is depicted in Fig.4.

The contribution to the spectrum $d\sigma/dm_{2\pi^-}$ corresponding to this graph of Fig.4 can be presented as:

$$\frac{d\sigma^{\Delta\Delta}}{dm_{2\pi^-}} = \frac{2m_{2\pi^-}}{(2\pi)^8 2\lambda^{1/2}(s, m^2, M_d^2)} \int ds_{\pi^+p} R_2(s, s_{2\pi^-}, s_{\pi^+p}) R_2(s_{2\pi^-}, \mu^2, \mu^2) \\ R_2(s_{\pi^+p}, m^2, \mu^2) \mid T_{\bar{p}d\to 2\pi^-\pi^+p}(s, s_{2\pi^-}, s_{\pi^+p}, t_1) \mid^2 \tag{7}$$

The amplitude $T_{\bar{p}d\to 2\pi^-\pi^+p}(s_{2\pi^-}, s_{\pi^+p}, t_1)$ corresponding to the graph of Fig.4 is written in the following form:

$$T_{\bar{p}d\to 2\pi^-\pi^+p}(s_{2\pi^-}, s_{\pi^+p}, t_1) = \phi_d^{\Delta\Delta}(p_\Delta) f_{\bar{p}\Delta^-\to 2\pi^-}(t_1) f_{\Delta^{++}\to\pi^+p}(s_{\pi^+p}) \tag{8}$$

where $\phi_d^{\Delta\Delta}(p_\Delta)$ is the part of the d.w.f. corresponding to the $\Delta\Delta$ component of Fock's column; $f_{\bar{p}\Delta^-\to 2\pi^-}$ is the amplitude of the process $\bar{p}\Delta^- \to 2\pi^-$; $f_{\Delta^{++}\to\pi^+p}(s_{\pi^+p})$ is the function corresponding to the down vertex of Fig.4, e.g., the decay of $\Delta^{++} \to \pi^+p$, and depending on the square of the invariant mass of the π^+p system s_{π^+p} . The form of $\mid f_{\bar{p}\Delta^-\to 2\pi^-} \mid^2$ can be found using the one-baryon exchange model, e.g.:

$$\mid f_{\bar{p}\Delta^-\to 2\pi^-} \mid^2 (t_1) = \frac{\mid t_1 \mid}{(\mid t_1 \mid + m^2)^2} F_2^2(t_1) \tag{9}$$

The function $f_{\Delta^{++}\to\pi^+p}(s_{\pi^+p})$ has the Breit-Wigner form and can be written as the following:

$$\mid f_{\Delta^{++}\to\pi^+p}(s_{\pi^+p}) \mid^2 = \frac{C}{(\sqrt{s_{\pi^+p}} - m_\Delta)^2 + \Gamma_\Delta^2/4} \tag{10}$$

where m_Δ is the Δ-isobar mass, Γ_Δ is its width, C is some constant. The form of the d.w.f. $\phi_d^{\Delta\Delta}(p_\Delta)$ taking into account the possible existence of a $\Delta\Delta$-component in the deuteron was taken from [1, 2] obtained within the framework of the quark model and had the following form:

$$\phi_d^{\Delta\Delta}(p_\Delta) = \sqrt{s_\Delta}\left(\frac{4b^2}{\sqrt{\pi}(3/2)^{3/2}}\right)^{1/2} exp(-b^2 p_\Delta^2/3) \tag{11}$$

where s_Δ is the so-called spectroscopic factor [1, 2]; b is the slope parameter [1, 2]. Now, inserting $R_2(s, s_{2\pi^-}, s_{\pi^+p}), R_2(s_{2\pi^-}, \mu^2, \mu^2), R_2(s_{\pi^+p}, m^2, \mu^2)$ and eqs.(8-11) into eq.(7) one can get the expression for the contribution $d\sigma^{\Delta\Delta}/dm_{2\pi^-}$:

$$\frac{d\sigma^{\Delta\Delta}}{dm_{2\pi^-}} = \frac{2m_{2\pi^-}\pi^3}{(2\pi)^8 2\lambda(s, m^2, M_d^2) 2\lambda^{1/2}(s_{2\pi^-}, \mu^2, \mu^2)} \int ds_{\pi^+p} \frac{\lambda^{1/2}(s_{2\pi^-}, m^2, \mu^2)}{2s_{\pi^+p}} \tag{12}$$
$$\frac{C}{(\sqrt{s_{\pi^+p}} - m_\Delta)^2 + \Gamma_\Delta^2/4} \int dt \mid \phi_d^{\Delta\Delta}(p_\Delta^2 \mid^2 \int dt_1 \mid f_{\bar{p}\Delta^- \to 2\pi^-}(t_1) \mid^2$$

Then, the total spectrum $d\sigma/dm_{2\pi^-}$ within the framework of the impulse approximation can be obtained as the incoherent sum of $d\sigma^{(1)}/dm_{2\pi^-}$ and $d\sigma^{\Delta\Delta}/dm_{2\pi^-}$, e.g.:

$$\frac{d\sigma}{dm_{2\pi^-}} = \frac{d\sigma^1}{dm_{2\pi^-}} + \frac{d\sigma^{\Delta\Delta}}{dm_{2\pi^-}} \tag{13}$$

The corresponding spectrum $dN/dm_{2\pi^-}$ calculated in the same manner as $dN/dm_{\pi^+\pi^-}$ and the OBELIX experimental data [11] are presented in Fig.3 (solid line). By the calculation of $d\sigma^{\Delta\Delta}/dm_{2\pi^-}$ the joint parameter value $s_\Delta * C^2$ has been found fitting the experimental data for $dN/dm_{2\pi^-}$ [11]. According to our calculations the spectrum $d\sigma^{\Delta\Delta}/dm_{2\pi^-}$ may contribute to the total spectrum at $m_{2\pi^-} = 1.4 - 1.5(GeV/c^2)$. Therefore, the small enhancement in $dN/dm_{2\pi^-}$ observed experimentally at $m_{2\pi^-} = 1.4 - 1.5(GeV/c^2)$, see Fig.3, can be interpreted as the contribution of $d\sigma^{\Delta\Delta}/dm_{2\pi^-}$.

At this point the question arises about the contribution of corrections to the impulse approximation of the annihilation process $\bar{p}d \to 2\pi^-\pi^+p$, see Fig.1. As for this possible correction, the two-step mechanism [17] can contribute to the spectrum $d\sigma/dm_{2\pi}$. Our estimations and the results of ref.[17] showed that this contribution is very small for the invariant mass value of π^+p $m_{\pi^+p} < 1.1 - 1.15(GeV/c^2)$ tha corresponds to $m_{2\pi^-} > 1.3 - 1.35(GeV/c^2)$ and can't give any enhancement at $m_{2\pi^-} = 1.4 - 1.5(GeV/c^2)$ to the spectrum $dN/dm_{2\pi^-}$, when according to [11] the momentum of the proton $p \geq 400\ MeV/c$. In principle, the two-step mechanism can give some sizeable contribution to this spectrum at $m_{2\pi^-} \sim 0.8 - 1.1(GeV/c^2)$. However, it is very difficult to calculate it accurately because there is a large uncertainty related to the off-shellness of the virtual meson in the intermediate state [18, 19]. Thus, according to the above this $\Delta\Delta$ component can contribute in the high mass kinematical region where the two-step mechanism of the annihilation process $\bar{p}d \to 2\pi^-\pi^+p$ can be neglected.

So, let us assume that a small enrichment in the $\pi^-\ \pi^-$ system invariant mass

distribution in the reaction $\bar{p}d \to 2\pi^-\pi^+p$ is a manifistation of the $\Delta\Delta$ component of the deuteron.

In this case, due to the lack of statistics, we can only obtain an upper limit for the process of Fig.4. Fig.5(a) shows the scatter plot for the invariant mass of the $\pi^-\pi^-$ system versus the invariant mass of the π^+p for $\bar{p}d \to 2\pi^-\pi^+p$ annihilation via the channel of Fig.4. There is a some small enrichment in the upper part of the π^+p system in the $\Delta^{++}(1232)$ region. In Fig.5(b), the invariant mass distribution of the $\pi^-\pi^-$ system in this reaction is shown. The solid line corresponds to all the selected events. The hatched histogram corresponds to the events with the invariant mass of the π^+p system satisfying the following condition: $|M_{\pi^+p} \; - \; M_{\Delta^{++}}| \; \leq \; 120 \; MeV$. As one can see, there is a small bump in the high mass part of the $\pi^-\pi^-$ invariant mass distribution, but this bump has a small statistical significance, so we can only estimate the upper limit for the reaction of Fig.4. To do this the distribution in Fig.5(b) was approximated at a first stage by a second order polynomial function. The parameters of this polynomial function were fixed and the experimental invariant mass distribution of the $\pi^-\pi^-$ system was fitted at the second stage by the function:

$$F \; = \; A_1 \; \times \; BW(\Gamma_{\pi^-\pi^-}, M_{\pi^-\pi^-}, m) \; + \; A_2 \; \times \; \sum_1^3 \; b_i \; \times \; m^{i-1} \tag{14}$$

where $BW(\Gamma_{\pi^-\pi^-}, M_{\pi^-\pi^-}, m)$ is the Breit-Wigner function. During the fit, the parameters $A_1, A_2, M_{\pi^-\pi^-}$ were free, the parameters of the polynomial function were fixed from the first stage of approximation and the $\Gamma_{\pi^-\pi^-}$ parameter was fixed at a value of 60 MeV according to theoretical prediction. Using the results of this fit, the upper limit on the reaction of Fig.4 was estimated to be:

$$Y_{\bar{p}\; (\Delta^-\Delta^{++}) \to 2\pi^-\pi^+p} \; \leq \; 6.5 \; \times \; 10^{-5} \tag{15}$$

with a 90% confidence level.

Finally, let us suppose that the branching ratio of the reaction $\bar{p}\Delta^- \; \to \; 2\pi^-$ is approximately the same as for $pN \; \to \; 2\pi$, that is $\simeq \; 5. \; \times \; 10^{-3}$ [21]. Using this assumption and the upper limit (15) we can roughly estimate the probability to find the deuteron as the $\Delta\Delta$ configuration. This probability is

$$P_{\Delta\Delta} \; \leq \; 1.\%$$

Note, that in the near future a factor of 10 higher statistics will be available for analysis from the OBELIX collaboration.

Let us now make a short conclusion on our investigation. Some enrichment of the scatter plot for $m_{2\pi^-}$ versus $m_{\pi+p}$ for the $\bar{p}d \to 2\pi^-\pi^+p$ process and the corresponding small enhancement in the spectrum $dN/dm_{2\pi^-}$ at $m_{2\pi^-} = 1.4 - 1.5(GeV/c^2)$ observed experimentally [11] can be caused by the possible existence of a $\Delta - \Delta$ component in the deuteron. The analysis of this phenomenon shows that it is difficult to calculate the absolute value of its probability. But the theoretical prediction about the width value of this enhancement allows us to estimate the upper limit for the $\Delta - \Delta$ exotic state of the deuteron.

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